LIGHTNING

The nature of the beast and how to survive its fiery fingers

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A short treatise on the nature of thunderstorms and the anatomy of lightning as far as it would be of especial interest to radio amateurs

by A. MARTINDALE, G3MYA*

Introduction

If, like my wife and I, you are one of the millions of people who show a certain amount of trepidation every time those black heaps of cumulo-nimbus loom large, read on. . . . . We live on one of the highest points in the small Suffolk town of Leiston, and we have had one or two close encounters of the charred kind since we moved here 26 years ago.

Our apprehension is fuelled by memories of an incident in 1959 when my top-band antenna became a lightning victim. We had been warned on the radio that there would be some electrical storms that day, so before I left for work I disconnected my equipment and grounded all the antennas. This seemed like a good idea at the time, and I was under the impression that this was the correct way to protect your installation from the ravages of lightning—how wrong can you be?

The predicted storms arrived after lunch, and did their thing with rain and heavenly pyrotechnics, and passed on their way. After the storm had gone by and the sun was shining, my wife looked out of the kitchen window to make sure the rain had stopped, and as she did so there was a most vivid flash accompanied by a tremendous crash and roar.

From what my wife told me when I got home, and from subsequent studies, I have no doubt that this was a positive lightning strike, which is the most violent type of all.

A quick inspection of the antenna system soon revealed a total absence of the top-band antenna and a close inspection of the ground revealed a few tiny copper balls—a direct strike! This unplanned metamorphosis of my antenna left me completely bemused and wondering how to protect my system from heavenly fireworks. I did not find an answer until comparatively recently, when the secretary of the Ipswich Radio Club suggested that I fill in some idle moments in a study of lightning and give a talk on protective measures to the members—that's how I got really interested.

The first problem I encountered was the difficulty of finding any suitable learned literature on the subject in the English language. My quest was eventually rewarded by my local library with a work by Dr R. H. Golde entitled *Lightning Protection* (Published in 1973 by Arnold at a (then) price of £6) to which I attribute most of the knowledge I have since acquired on the subject.

Thunderstorms—their formation and performance

In order to face an enemy, it is always a good idea to have a basic understanding of his physiology and habits—in military parlance this is called an "appreciation"—so I will start this appreciation with the lightning's home base—the thunderstorm itself.

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In the UK, thunderstorms fall into two basic categories which have quite different beginnings and are not readily confused with each other. Both are the result of very turbulent air which, by its very nature, collects electrical charges from frictional contacts within the air itself, with surrounding objects, and with water vapour in particular. These charges distribute themselves in a very orderly manner throughout the storm centre so that the top of the storm is positively charged with respect to its base.

The first of the two categories is the "frontal" storm that heralds the arrival of cooler air on a cold front. It is triggered by the sudden upheaval of warm, surface air by the approaching cold air. This has the effect of lifting the warm air very quickly and creating an assisted thermal situation as the warmer air is replaced by the advancing cold air. All this activity is quite violent and frequently creates a "squall-line" that is often accompanied by quite severe, but short-lived electrical activity.

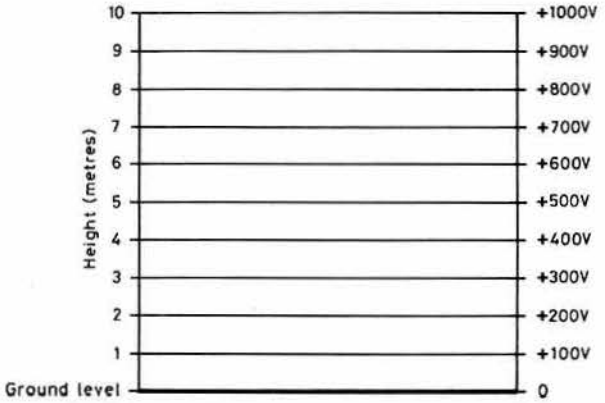

Fig 1. The normal voltage gradient on the bottom 10m of the atmosphere on a normal, warm summer's day

The more familiar type of storm is the one that appears late on a summer's afternoon and seems to hang around for hours grumbling and banging for what seems to be an age. These summer storms are again the result of rising warm air, but this time not assisted by the approach of cooler air. This time the rising air is the result of summer heat over warm, moist ground creating thermals beloved of gliding enthusiasts. These thermals, however, are really quite fierce. They rise to many thousands of feet and lift huge quantities of water with them in the form of vapour, which condenses as it cools and forms those massive thunderheads known as cumulo-nimbus. This massive conglomeration of thermals is due to the fact that there is not usually much wind at the time, thus allowing these thermal columns to become much more concentrated. This lack of wind also accounts for the fact that summer storms tend to hang around for some time.

Both types of storm produce lightning of all descriptions. Frontal storms seem less active, but this is mostly due to their rapid transit over the ground and the fact that the line of storms is at right angles to the passage of the front, thus allowing storm activity to pass relatively quickly. The summer storm, however, moves very slowly, is usually much larger—covering a greater ground area—and contains more than one storm centre to each storm.

Lightning—what it is, how it is produced, and types of stroke

While it is not easy to quantify all the components of a lightning stroke, a lot of research has been done, and by a combination of scientific measurement and educated observation it has been possible to come up with some interesting figures. For instance, the average peak current in a cloud-ground stroke is about 25kA. That is for a negative stroke, but the sort of current encountered in a positive stroke has been known to peak at over 270kA!

When it comes to measuring the actual amount of electricity discharged in a single stroke, the task is much more difficult, but certain scientific techniques have come up with some very reliable figures, based on measurement and calculation. For instance, by measuring the damage to aircraft or other metal surfaces, it is possible to re-create the same current in a controlled discharge and, by measuring the distance of travel and dissipation of heat en route, to come up with a reasonable estimate. From these and similar measurements, such as oscilloscope traces measuring current in certain selected lightning conductors, it is estimated that the

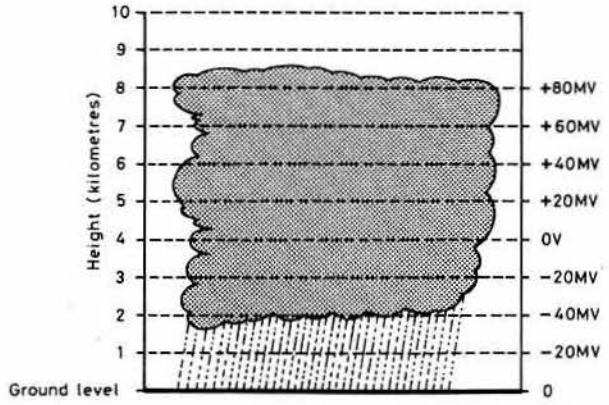

Fig 2. The average voltages encountered in the bottom 10km of the atmosphere in the area of an active thundercloud

average total discharged during the life of a single storm centre is around 1,000 coulombs. With an average of about 20 to 30 discharges per storm centre, this would put an average stroke's total discharge at around 40 coulombs. If we assume the average storm centre to resemble a capacitor of about 25μF, with a charge of 1,000C the charge potential will be of the order of (V = Q/C) 40MV. To put this into perspective as potential energy, it represents an energy of 40GJ or (in terms of the domestic electricity supply) enough latent power to supply the average household for two years. Remember that one storm can, and usually does, consist of several storm centres.

One aspect of thunderstorms which can be measured accurately is the voltage gradient between cloud and ground, and results of research in this field (no pun intended!) produce some hair-raising figures (that pun *was* intentional!). On any day of the year there is always a space charge between the ground and the atmosphere, with the ground normally being negatively charged with respect to the air above it. On a warm, summer day this charge is around 100V/m, somewhat less on a cooler day. These figures go completely haywire when there are thunderstorms about!

As mentioned earlier, a thunderstorm carries a heavy static charge with positive at the top and negative at the bottom. In fact, the base of the thundercloud becomes so negatively charged that it is much more negative than the ground, thus reversing the normal voltage gradient and doing it in a most convincing way. With the base of a thundercloud at about 2km above ground and the top some 6–7km high, it is the charge across the bottom 2km that most interests us at this stage.

As a charged-up cu-nim approaches, the standing voltage gradient declines, momentarily disappears and then reappears with reversed polarity and increases very quickly. When the storm centre is still some 5km distant, the voltage gradient has climbed to 5,000V/m, and directly beneath the storm centre it rises to a shocking 20,000V/m! It is when this gradient gets so steep that you feel its effects by your hair "standing on end", and at the same time sweat glands are stimulated.

Looking at the voltage gradients, Fig 1 shows the gradient on a normal summer day, and Fig 2 the gradient under and in a thundercloud over flat ground. In residential areas of course, flat ground is broken by obstructions such as trees and buildings (not to mention our antennas!) and Fig 3 shows the effect of obstructions in the electrostatic field between cloud and ground. Where an obstruction occurs, there is some local compression of the voltage gradient, especially at the corners of electrically-earthed structures and other protrusions. Flagpoles, masts and chimneys all tend to cause tight compression and the effects of this will be discussed later. Fig 4 shows the extreme compression of the voltage gradient at the tip of a very sharp pointed object, such as a lightning conductor, and it will be seen how easy it is to get a breakdown of the insulation factor of air. This results in local ionization, which appears as a pale blue glow and is sometimes called St Elmo's Fire. Another place where one can see ionized air in connection with a thunderstorm is along the leading edge of a very active squall line, but this pale blue line is not often visible.

Now to the actual anatomy of lightning itself, and there is literally more to this than meets the eye! For our example we will take the common ground stroke, known as the negative stroke because it originates in the negative region of the cloud, and which is the most documented of all the lightning phenomena. As explained above, there is already a steep voltage gradient between the base of the cloud and the ground, though this in itself is not sufficient for the insulation property of air to break down and the air to ionize—it needs some help. Beneath the cloud is an area of extreme turbulence, and this is constantly causing local high charges to be

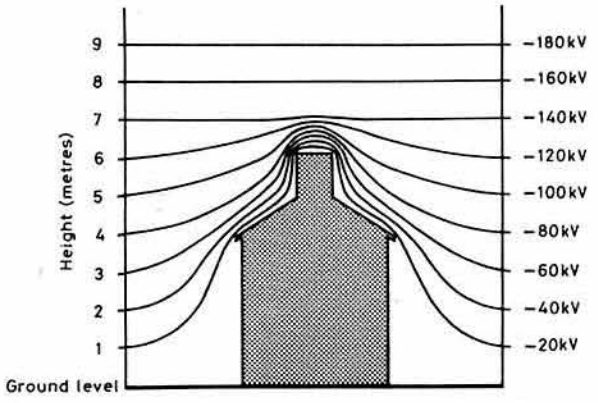

Fig 3. The effects of the high voltage gradient beneath a storm centre on ground obstructions. Note the tight bunching at chimney corners

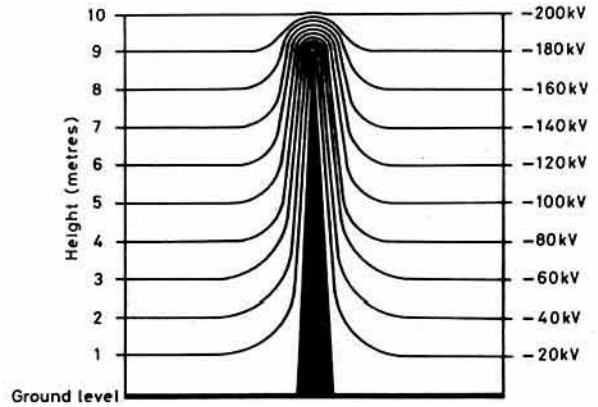

Fig 4. The effect of a tall, sharp object in the high voltage field beneath an active storm centre. The tight bunching often leads to a local breakdown of air insulation at the tip, causing ionization at that point

generated. This causes separation of air molecules, and the positively-charged ones (those that have temporarily lost an electron) are lighter and travel upwards towards the highly negatively charged cloud base. This, in turn creates local imbalances in the overall voltage gradient and suddenly there is a path of about 20m where the gradient is so steep that ionization occurs between a point at the cloud base and a positively-charged packet of air about 20m or so below it. This ionized path now brings the cloud base potential down by 20m at the leader tip (the ionized track is called the leader). This means that another packet of positively-charged air within about 20m will cause the leader to continue its course—possibly two more packets will be targets for the leader, which will split as many ways as it pleases. Not all leader tips continue to find sufficient targets on which to continue, so they just fizzle out, while the more prosperous ones continue on their erratic path towards the ground (see Fig 5).

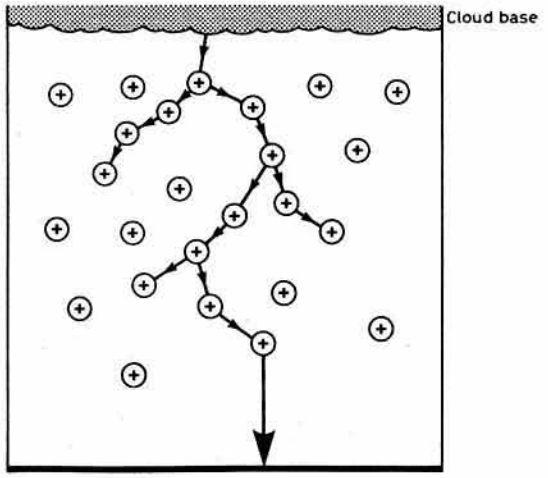

Fig 5. Track of a leader, showing its movement to the nearest positive air packet, and dying leader tips

In addition to the positively-charged packets of air caused in the under-cloud turbulence, there are also packets being formed by local ionization down at ground level—where small coronal discharges are taking place at the tips of lightning conductors and other projections. All these little packets rise and join the throng, making sure that there is a steady supply of "tag-points" for the leader tip. Eventually, this tip reaches a point about 40m above the ground. As the leader is a track of ionized air, it has a very low resistance, so it effectively brings the potential of the cloud base to a point just 40m from the ground.

So far, the leader has been travelling downwards from the cloud base at a velocity of around 10^5m/s, and is clearly visible as a pale blue, jagged, luminescent line. The reason we do not actually notice it is because it only takes about two thousandths of a second to complete its downward path before it is totally outshone by the main discharge. But, before that can happen, one final leap is required to complete the ionized path between the cloud and the ground. From its vantage point some 40m above the ground, the leader tip selects the shortest (electrical) path to ground potential and bridges it with the final bit of ionization to complete the circuit between cloud and ground.

We now have a low resistance connection between two points of many megavolts, and the only thing that can possibly happen is that a current will flow in an effort to neutralize that potential difference. The main discharge actually travels in the opposite direction to the leader, ie from the leader tip via the shortest electrical route back to the point of origin of the leader. The actual amount of current depends on the resistance of the path and the potential across it (Ohms Law). If it had its way, the discharge would be a perfect square wave, but the ionized path, being a single conductor of finite length, also has inductance. This inductance shapes the return stroke, thus allowing it to build up to maximum as it generates a colossal magnetic field around it, and dying away as the field collapses at the end of the discharge. Fig 6 shows the profile of a ground stroke (negative) as measured on a special lightning conductor connected to an oscilloscope. Even so, the leading edge of the return stroke (as the main discharge is called) reaches the cloud just 22 ten-thousandths of a second after the leader started its downward journey. To put it another way—it's all over in a flash!

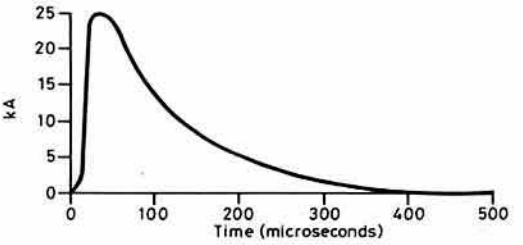

Fig 6. Profile of a negative ground stroke

In the introduction I mentioned a positive ground stroke which made itself known to me in 1959. When a storm cloud is almost spent, there is less electrical activity as most of the charge has been discharged, either to ground or between clouds. The internal turbulence dies down and the positively-charged air tends to mass at the top of the cloud. This now creates a new situation where the main potential difference appears, not at the base of the cloud, but at the top; this is all the residual charge, which amounts to something like almost half the original charge. As the top and base of the cloud tend to travel over the ground at varying speeds, there sometimes comes a point when the easiest way to discharge this huge charge at the top of the thunderhead is to do so to ground rather than in the cloud itself. This creates a positive stroke and works in exactly the reverse order to the more common negative stroke, with the leader starting its journey from the ground and the return stroke actually travelling the commonly-thought route from cloud to ground. This is the mighty "tail-ender" that often takes you by surprise when you think that a summer storm has safely passed. A profile of the positive stroke appears in Fig 7.

Another variant of the common negative ground stroke is the multiple stroke, and it also has an interesting anatomy. It starts out in exactly the same way as a normal negative ground stroke, but one return stroke is not enough to neutralize the potential across the leader track. With all the tubulence and the damage caused by the return stroke, the track needs re-ionizing in order to permit a further discharge. A fresh leader sets out and follows the remnants of the original path for most or all of the way, creating a freshly-ionized track for a further discharge. This new leader travels much faster than the first one, at the same speed as the main return stroke, in fact, and it is known as a "dart leader". However, during the course of a multiple stroke, the entire storm is travelling laterally and it quite often happens that—after a few multiple strokes—the next dart leader finds a

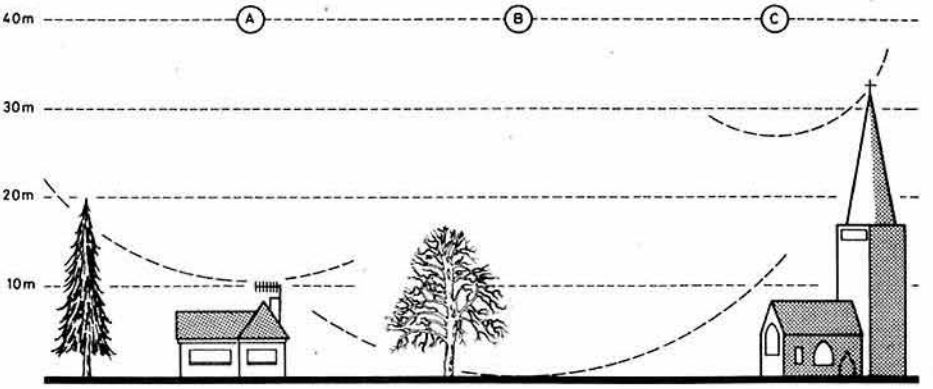

Fig 8. Three alternatives for the leader to find its final track to ground. At "A" the fir tree and the tv antenna are most at risk; at "B" the round tree or the ground itself seem most likely, while at "C" the top of the church spire is an obvious choice. The significant thing is that prior to arriving at these three points, ground conditions have little effect on the track

more acceptable ground target so that it ionizes a fresh path for the next and subsequent discharges. To the unaided eye this looks as if the lightning has split and struck two or more places at the same time. This is not so, but because the strokes are in such quick succession it looks like a split stroke. This is what is commonly known as "fork-lightning", for obvious reasons. Up to 26 succesive discharges have been recorded in a multiple stroke, taking almost half a second to complete.

Going back to our primary leader for a moment, it might help to put things in perspective if we take a further look at the last 40m when the final breakdown of the remaining gap occurs. As the last leap is over a distance of about 40m, and the actual insulation breakdown point of air is between 3 and 5kV/cm, a short calculation based on 4kV/cm gives a breakdown voltage between leader tip and ground of about 16MV! That is a fair old "tickle" in anyone's language, and it helps one to realize just how insignificant are man's efforts when compared with nature's gentler activities. Incidentally, cloud-to-cloud strokes are thought to resemble negative ground strokes, but it is difficult to verify this. The common name for cloud-cloud strokes is "sheet lightning".

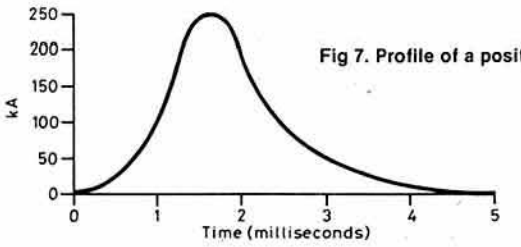

Fig 7. Profile of a positive ground stroke

Other factors which influence the strength of a lightning stroke are the nature of the ground potential at the point of strike. This means the physical nature of the object struck—its conductivity and the conductivity of the ground connected to it. For instance, a chimney that has not been used and is dry is not a very good conductor, but one that has been used and contains an internal coating of soot (carbon) is a good conductor and is more likely to attract a direct strike. Likewise a tree in winter when the sap is low is not so attractive as it is in the summer when it is full of sap and greenery.

Fig 8 shows how a leader selects its target for the final connection of the ionized track; it would be better if it could be shown in 3-D, but a cross-section of typical ground gives some idea of the situation. The important thing is that when the leader tip reaches the 40m point it will immediately go on to the most advantageous ground potential, and that means the point of least resistance (including the intervening air) and that normally means the highest point at earth potential within striking distance. Down to the 40m point from the cloud base it is not affected so much by what is on the ground, unless that ground structure is giving off a good supply of ionized air packets to guide the leader in.

Some facts and figures on thunderstorm activity in the UK

In assessing the need for protection from electrical storms, the following information may help to make up your mind—or, conversely, it may only serve to confuse you even further! By scientific observation it has been established that, on a nationwide basis, there are 10 days in the year when there are thunderstorms in the vicinity of any one place. They need not be directly overhead, only within clearly audible range. Of course this is an average which is subject to differences in location and counts from year to year, but these figures have been calculated over a long period and from a large variety of locations. My own recollection seems to differ quite substantially from this, but then mine is subjective while the quoted figures are objective.

Allowing for the fact that not all storms are overhead and that most storms consist of more than one storm centre, it is calculated that 10 storm centres pass directly overhead in any one year (on average!). However, seasonal variations, preferred storm paths and other stray phenomena could double this figure, so we will assess the risk on the basis of 20 storm centres passing overhead per year.

In the UK and similar temperate regions, each storm centre produces about 20 or 30 strokes during its average life of 30 to 60min. Of these strokes, less than half (about 40 per cent) are cloud to ground strokes, and of these ground strokes about 95 per cent are negative type.

Each storm centre covers a ground area of about 4km². If the storm centre were to remain perfectly stationary during its active life, it would produce 2·5 ground strokes/square kilometre, but on average a storm centre travels across the ground at a speed of 50km/h so its ground strokes are distributed over an area of 100km². This gives an average of 0·1 ground strokes/storm centre/square kilometre. Multiply this by 20 storm centres/year and this leaves us with two ground strokes/square kilometre/year.

Now let us take a look at an average domestic property of about 20 × 50m or an area of 1,000m². One thousand such properties would fit into 1km², which means that the chances of a direct strike on a single property works out at once every 500 years! We all know what happens to averages and statistics, but I think it is wise to try and get the whole thing into perspective.

Of course, radio amateurs do tend to tempt providence a bit by putting things up high in the sky with good electrical connections to a point not too dissimilar from earth potential—this must increase the risk of a strike on our property, to the relief of our neighbours! If, in our quest for better radio communications, we do put up such electrically attractive devices, it is in our own interest to do something to protect them.

This article is not intended to deal with protection, but one method is worthy of note, because it is simple and offers 93 per cent protection to all your antennas and house etc from a direct strike. This device consists of a single mast of sufficient cross-sectional area to stand (guyed if necessary) in the centre of your property and be 5m higher than any other part of the installation. Top off this mast with a short length of copper rod not less than 25mm², with a sharp point on the top and very securely fitted to the mast with an excellent electrical connection, and fully protected against corrosion. All joints on the mast must be the same. The mast ought to be of 2in diameter aluminium or similar.

The base of this mast should be connected to an earth rod of 0·5in galvanized pipe or, better still, hardened copper rod or "T" section earth rod. This should be not less than 8ft long for normal ground, but in poor conditions two or more spikes or one much longer spike should be used.

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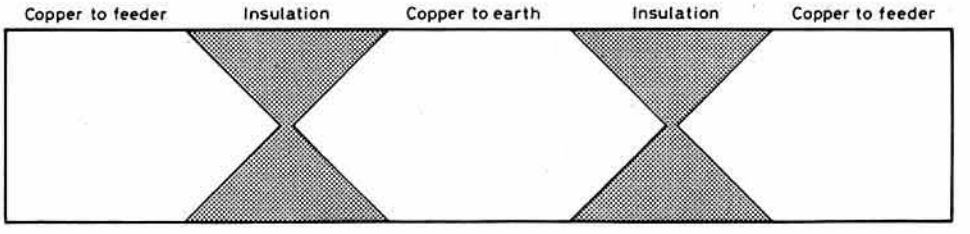

Fig 9. This is the exact size of the author's spark discharger, which is made from a piece of pcb with the copper either stripped or etched away from the shaded parts. The centre is earthed and the two sides are connected to the feeder

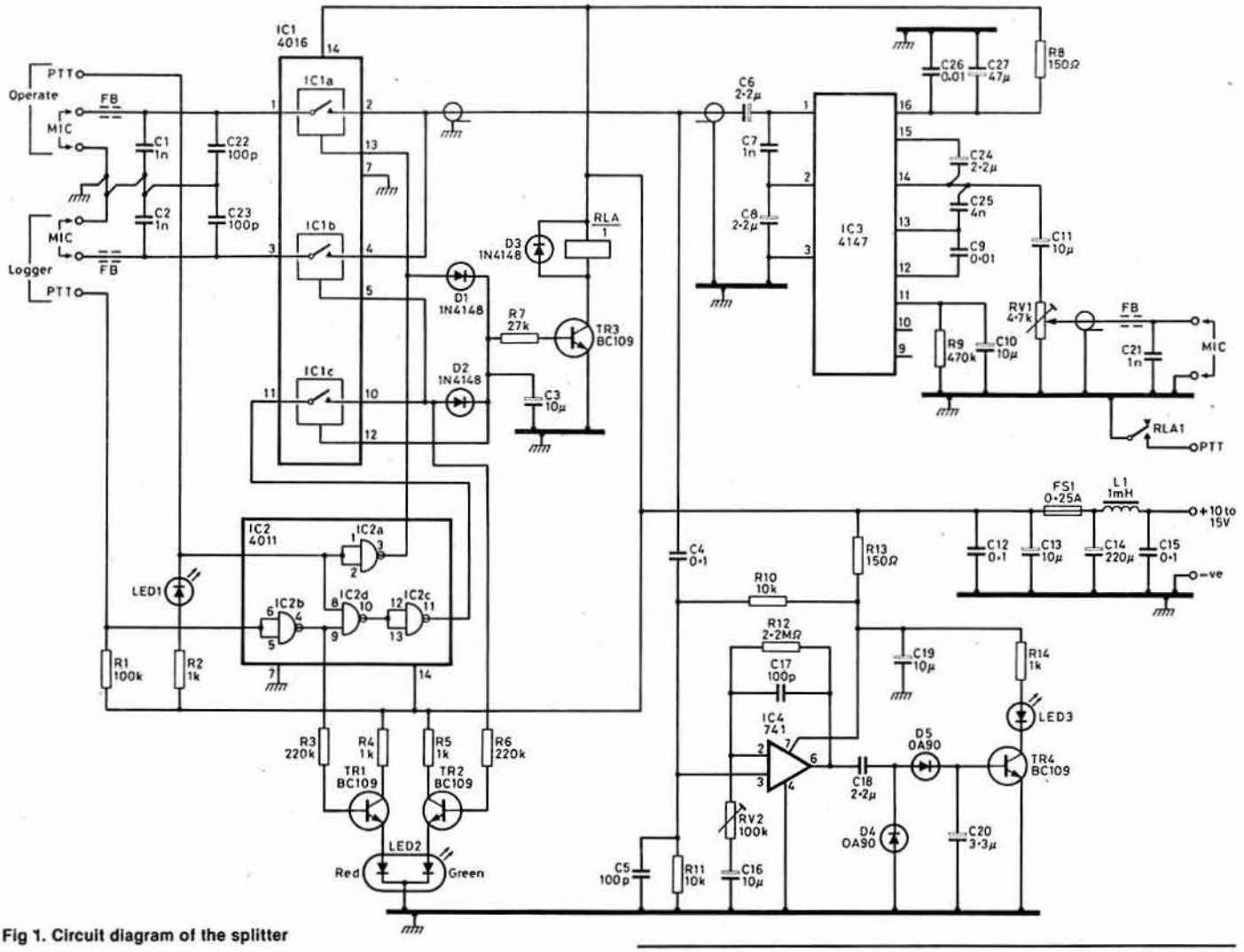

Fig 1. Circuit diagram of the splitter

therefore not essential; it was the main reason for the rf problems experienced. In fact, for the 1982 JOTA, IC3 was bypassed in order to overcome the trouble with the rf (most of the decoupling and ferrite-beads were added when IC3 was reconnected to the circuit).

Setting-up

There are only two adjustments. The first sets the level of the speech into the transceiver by means of RV1, which should be set so that the audio level of the transceiver is the same as it is with the splitter not connected. The second adjustment sets the point at which the modulation level indicator comes on, by means of RV2, which should be set so that LED3 just comes on when the microphone is modulated normally.

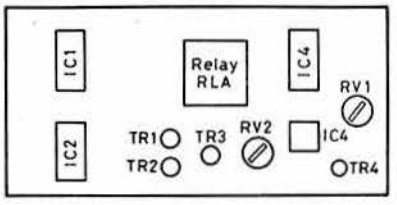

Fig 2. Veroboard layout

Both these adjustments can be done with an oscillator and oscilloscope, but if none is available they can successfully be done by whistling or giving an "AAAAR" into the microphone and watching the o/p on ssb, or by listening to the audio level on a receiver with fm. □

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This mast will provide a cone of protection for all equipment within a radius of 20m or a circle 130ft across. This mast has one other advantage of most interest to the hf operator. It can be gamma matched and used for low-angle radiation on the hf bands, and if it happens to total 66ft high, then 3·5MHz dx will be a doddle! Without doubt, this is one of the best and most efficient lightning protection systems yet devised for the radio amateur, without spending a vast fortune for possibly one per cent more than the 93 per cent region of protection.

Conclusion

A final word on protective devices. Another thing the average amateur can do for himself is to make a simple spark-gap discharger to fit on to the downleads of his antenna systems. Fig 9 shows details of the one which I made for use on open-wire feeders. A different design, but of the same principle, will suit coaxial feeders, the objective being to avoid turning your antenna system into grounded lightning conductors. If your antennas are all well insulated from ground, a charge will build up on them in the presence of a storm; this will result in high voltages both at the top and bottom end of the feeders. The spark discharger will take away most of the high voltages present on the feeders without grounding them, and without interfering with their effectiveness as feeders.

All this protection and knowledge does not take away the potential of the emp (electro magnetic pulse) which is generated by all types of lightning stroke, and these "spikes" can seriously damage the health of solidstate devices in the front-ends of receiving equipment. A little care is needed to deal with this problem, but that is outside the province of this article. □